

## **MEMS Technology at NASA's Jet Propulsion Laboratory**

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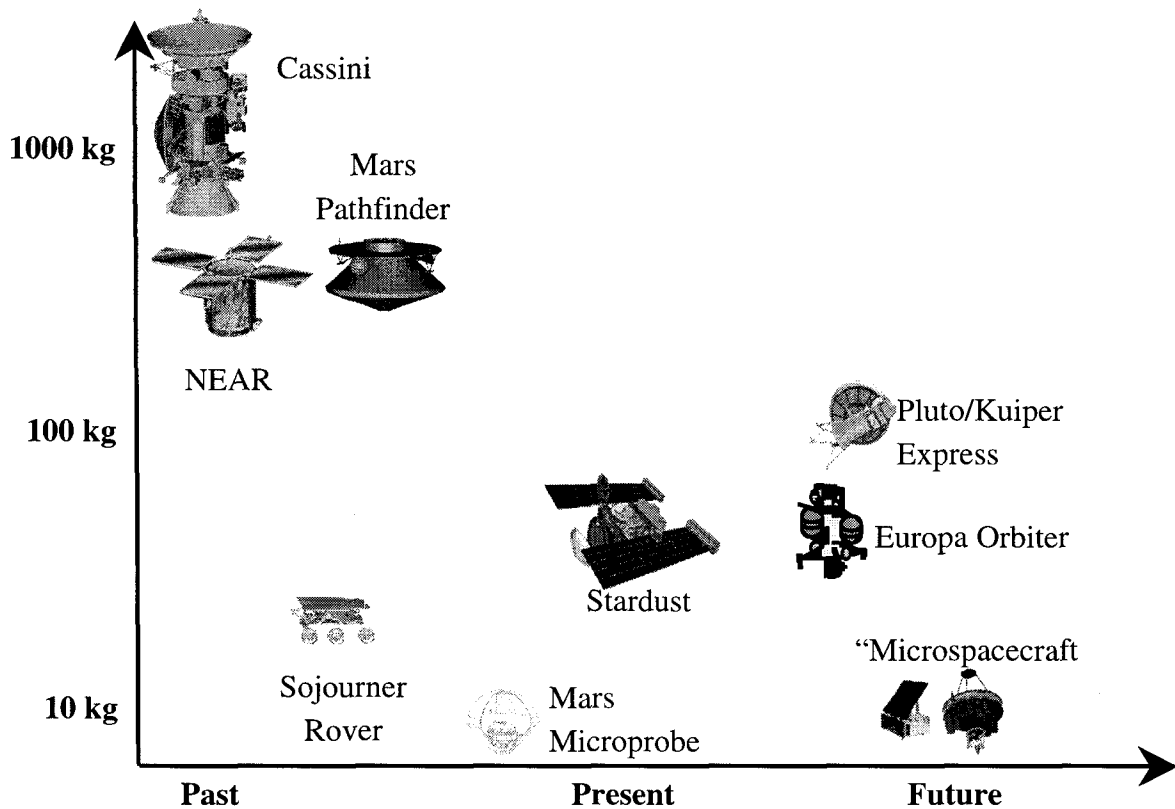
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### **Abstract**

The MEMS Technology Group is part of the Microdevices Laboratory (MDL) at the Jet Propulsion Laboratory (JPL). The group pursues the development of a wide range of advanced MEMS technologies that are primarily applicable to NASA's robotic as well as manned exploration missions. Thus these technologies are ideally suited for the demanding requirements of space missions namely, low mass, low power consumption and high reliability, without significant loss of capability. End-to-end development of these technologies is conducted at the MDL, a 38,000 sq. ft. facility with approximately 5500 sq. ft each of cleanroom (class 10 – 100,000) and characterization laboratory space. MDL facilities include computer design and simulation tools, optical and electron-beam lithography, thin film deposition equipment, dry and wet etching facilities including Deep Reactive Ion Etching, device assembly and testing facilities. Following the fabrication of the device prototypes, reliability testing of these devices is conducted at the state-of-the-art Failure Analysis Laboratory at JPL. Some of the key MEMS technologies being developed currently by the group include a vibratory microgyroscope, LIGA-based devices, micro-propulsion devices, micro-valves, adaptive optics, micro-actuators, biomedical devices, system-on-a-chip, micro-instruments and packaging. Future growth areas for the MEMS group are expected to be in the areas of nano-technology and bio-technology.

### **Introduction**

The Jet Propulsion Laboratory (JPL) has the charter for designing and implementing robotic, planetary exploration missions for NASA. During the past decade, NASA's planetary exploration strategy has evolved from sending a few, very large (1000 kg and above) missions that each took several years to develop, to the "smaller, faster, cheaper" approach of launching multiple microspacecraft requiring far shorter development times (Fig. 1). The Microdevices Laboratory (MDL) at JPL was set up as part of the Center for



**Figure 1.** The evolution of NASA planetary exploration platforms. Cassini was the last of the ~1000 kg class spacecraft that took over a decade to build. The future trend is towards having multiple microspacecraft missions with far shorter development times. In order to insure that miniaturization does not automatically imply loss of capability, novel devices and instruments based on MEMS technology are required.

Space Microelectronics Technology, in order to support the need for advanced micro-technologies by NASA and DOD agencies. MEMS activities at the MDL began in the late 1980's with the work of Kaiser, Kenny and coworkers<sup>1,2</sup> when they developed Si bulk-micromachined, electron-tunneling sensors such as an accelerometer, a thermal infrared detector and a magnetometer. The group has since grown to take on a diverse range of activities in support of NASA's needs for MEMS-based devices and instruments. The facilities available at the MDL as well as a few key activities of the MEMS Technology Group are described in brief below:

### **Microdevices Laboratory Description**

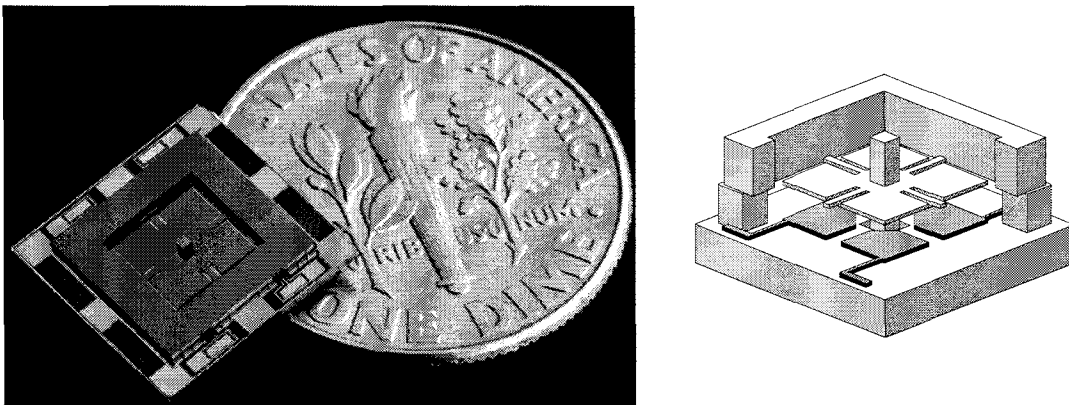
The Microdevices Laboratory is a 38,000 square foot facility with around 5,500 ft<sup>2</sup> each of clean room processing and device characterization laboratory space. The cleanrooms are partitioned into four categories: class 10, class 100, class 1000 and class 100,000. The MDL is equipped to provide end-to-end fabrication, characterization and rapid prototyping of silicon, compound semiconductor and superconductor devices. The facilities available at the MDL include the following:

- **Lithography:** High resolution ( $<0.1\ \mu\text{m}$ ) electron-beam lithography, 5X stepper, and double-sided contact aligners.
- **Material deposition:** Molecular Beam Epitaxy (MBE) with in-situ characterization (RHEED, XPS, and Auger Spectroscopy), Organo-Metallic Vapor-Phase Epitaxy (OMVPE), Magnetron and Diode sputtering, E-beam and Resistive Evaporation, Electron Cyclotron Resonance (ECR) Deposition, Low-Pressure Chemical Vapor Deposition (LPCVD), Plasma Enhanced Chemical Vapor Deposition (PECVD), oxidation and diffusion.
- **Feature patterning:** Acidic and alkaline wet etching, plasma and reactive ion etching, ion milling, and Deep Reactive Ion Etching (DRIE).
- **Post-process packaging:** Wire bonding, die separation, die attach, flip-chip aligner/bonder, and fusion/anodic/eutectic/ thermo-compression bonding.
- **Surface and interface characterization:** Scanning Tunneling Microscopy (STM), Ballistic Electron Emission Microscopy (BEEM), Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), Electron Spectroscopy for Chemical Analysis (ESCA), and X-ray diffraction.
- **Thin-film characterization:** Ellipsometry, stylus profilometry, optical microscopy, and interferometry.
- **Bulk electrical and optical characterization:** Photoluminescence (VIS, IR), four-point resistivity probe, spectrophotometry, I-V/C-V measurement, Hall measurement, and Fourier Transform Infrared Spectroscopy (FTIR).

### **MEMS Technology Group Activities**

The MEMS Technology Group undertakes a diverse range of projects which include the development of inertial sensors such as vibratory microgyroscope, LIGA-based devices, micro-propulsion devices, micro-valves, adaptive optics, micro-actuators, biomedical devices, system-on-a-chip, micro-instruments and packaging. A selected few of these projects are described below.

**Vibratory Microgyroscope:** The development of the MEMS Microgyro<sup>3,4</sup> (Fig. 2) is in



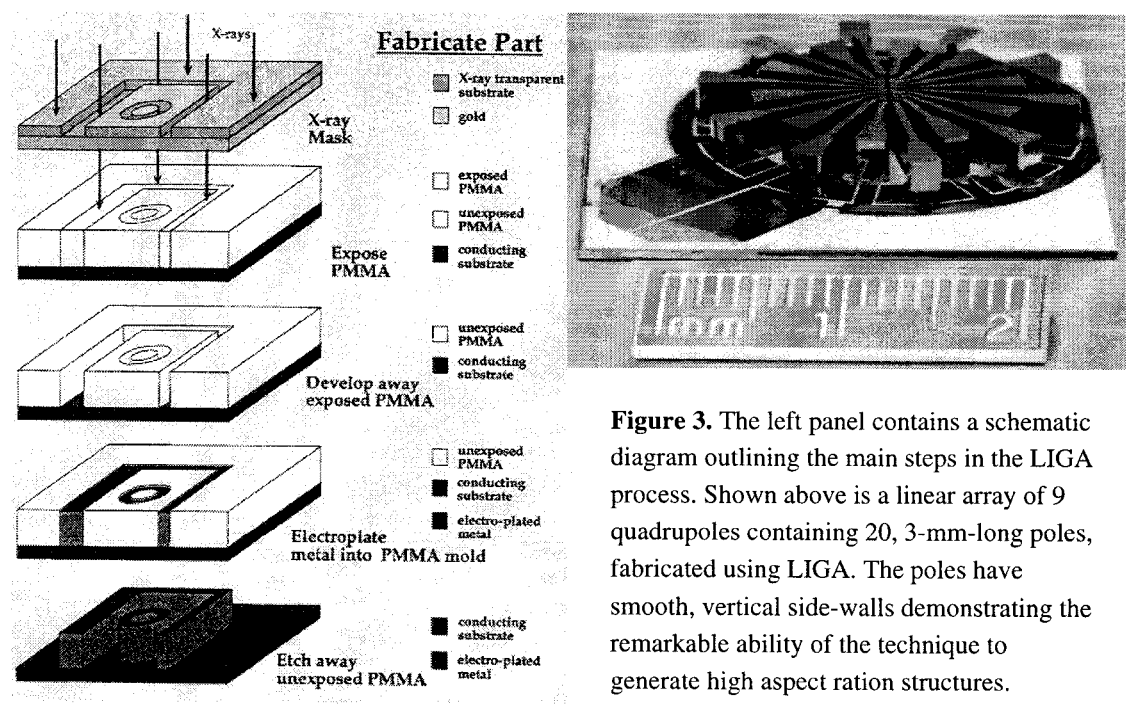
**Figure 2.** Integrated MEMS Microgyro device, based on a symmetric “clover leaf” design senses the rotation about the axis of the central post. The “petals” of the clover leaf are suspended on two orthogonal beams that form the torsional spring elements. The device operates by rocking the petals about one beam and sensing the Coriolis force due to the rotation by measuring the differential capacitance between adjacent petals across the other beam.

response to a NASA need for highly miniaturized inertial sensors for Guidance, Navigation and Control on a variety of micro-mission platforms ranging from orbiters around Neptune to landers on Europa to rovers and sub-surface explorers on Mars. The goal of the Microgyro project is to produce high performance, low cost, reliable MEMS gyroscopes that can be integrated with a system-on-a-chip architecture. In the five years since the inception of the project, impressive technological strides have been made in the improvement of the Microgyro design, optimization of the fabrication process, as well as in the techniques used for the testing and characterization of the device. The experimental setup and testing protocols for gyroscope automated testing (GAT) and device lifetime testing (DeLiTe) procedures have been established. The current performance of the Microgyro is summarized in Table 1.

**Table 1.** MEMS MicroGyro Performance Goals and Current Status

<i>Parameter</i>	<i>Goal</i>	<i>Current Status</i>
Bias stability:	<0.1 deg/hr	<0.3 deg/hr
Angle Random Walk:	<0.01 deg/rt-hr	<0.095 deg/rt-hr
Scale factor drift:	<50 ppm	
Bandwidth:	>100Hz	

**LIGA-based Device Development:** The MEMS Technology Group has made significant investments into the development of an infrastructure for the fabrication of high-aspect ratio structures by LIGA processes<sup>5</sup>. LIGA is a German acronym derived from Lithographie, Galvanoformung and Abformung which are interpreted as lithography, electroplating and replication. It is an X-ray lithography technique in which a thick (~100 microns) Poly Methyl Methacrylate (PMMA) resist is exposed to x-ray radiation from a



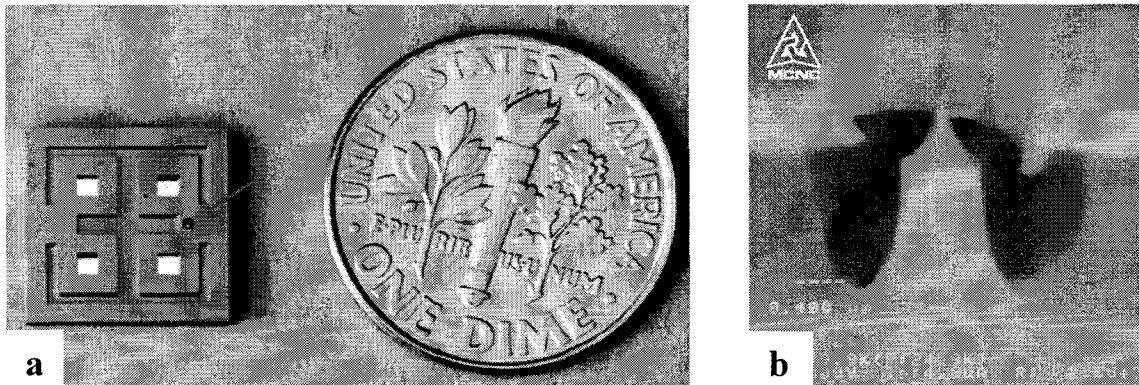
**Figure 3.** The left panel contains a schematic diagram outlining the main steps in the LIGA process. Shown above is a linear array of 9 quadrupoles containing 20, 3-mm-long poles, fabricated using LIGA. The poles have smooth, vertical side-walls demonstrating the remarkable ability of the technique to generate high aspect ration structures.

synchrotron source. The PMMA is then developed to create a mold into which metals are electroplated (Fig. 3). The plated metal structure can be used as a final part or as the basis for further replication using techniques such as injection molding. The LIGA effort has been setup as a consortium between JPL, the Lawrence Berkeley Laboratory and the Sandia National Laboratory at Livermore, CA. Additional synchrotron facilities that are utilized include the Stanford Linear Accelerator Center and the facilities at Brookhaven National Laboratories. The LIGA process has been used successfully to fabricate microwave waveguides for the EOS-Microwave Limb Sounder mission. Also shown in Figure 2 is a LIGA-fabricated linear quadrupole array for a miniature mass spectrometer. Current LIGA projects include the fabrication of a miniature ion trap for a mass spectrometer, a meso-scale gyroscope and a miniature scroll-type roughing pump. The ion trap and gyroscopes require novel 3-dimensional structures that will be attempted using LIGA.

**Micropropulsion Devices:** The Advanced Propulsion Group at JPL is spearheading the development of MEMS-based propulsion devices in collaboration with the MEMS Technology Group. MEMS-based propulsion systems offer the advantage of being easily integrated with drive electronics and other MEMS devices such as valves, resulting in reductions of several orders of magnitude in mass and volume over conventional systems as shown in Table 2.

**Table 2.** Comparison of performance parameters for typical small scale conventional systems vs MEMS propulsion systems

Performance Parameter	Conventional small scale system	MEMS propulsion system
Mass	10 – 20 kg	10 – 100 g
Volume	0.1 – 0.5 m <sup>3</sup>	1 – 10 cm <sup>3</sup>
Thrust	~ 1N	0.1 – 5 mN
Impulse Bit	~ 1 mNs	1 – 100 $\mu$ Ns
Power Consumption	10 – 20 W	1 – 5 W



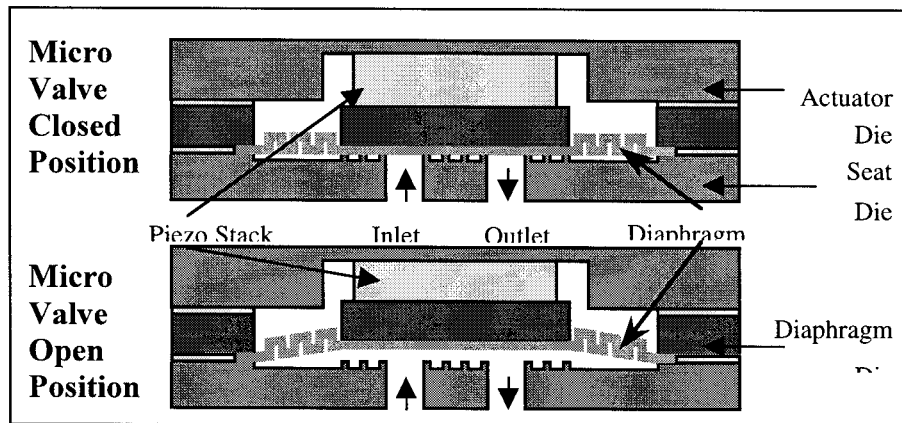
**Figure 4.** (a) A Vaporizing Liquid Microthruster chip with the arrow pointing to the exhaust nozzle. The larger openings are for wirebonds to be made to the resistive heaters. (b) Cross-sectional view of a single silicon field emitter fabricated by MCNC, showing the post-shaped cathode and the annular gate electrode surrounding the emitter tip.

Two MEMS-based micropropulsion concepts being currently developed by the team are a Vaporizing Liquid Microthruster (VLM)<sup>6</sup> and a Micro-Ion Engine. The VLM contains liquid propellant that is pressure fed to a cavity containing a thin-film heater assembly. The propellant is vaporized by the heater and exhausted through nozzles to produce thrust. The VLM (Fig. 4a) is an extremely small and light thruster with compact liquid propellant storage. It is amenable to on-chip integration schemes and is scalable to provide very small thrust and impulse bits for attitude control applications. The Micro-Ion Engine employs Field Emitter Arrays (FEAs) (Fig. 4b). A Cathode Lens and Ion Repeller (CLAIR) structure has been designed for the Micro-Ion Engine and is currently under fabrication.

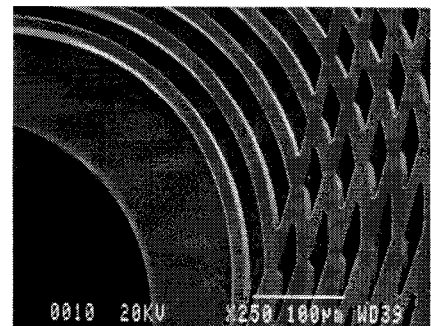
**MEMS Microvalves:** The major stumbling block for MEMS-based microfluidic devices such as Microthrusters is the lack of good MEMS-based valves that can be integrated into these devices. In the case of the Microthruster devices the requirements for these valves can be very demanding as shown in Table 3.

**Table 3.** Microvalve requirements for MEMS-based Microthrusters

Performance Parameter	Desired ranges
Leak Rate	< 0.3 sccm <sup>3</sup> /hr Helium
Actuation Speed	< 10 ms
Inlet Pressure (liquid)	0 – 300 psia
Inlet Pressure (gas)	0 – 3000 psia
Power Consumption	< 1 W, 5 V
Valve mass	< 10 gm
Operating Temperature	-120 °C to 200 °C

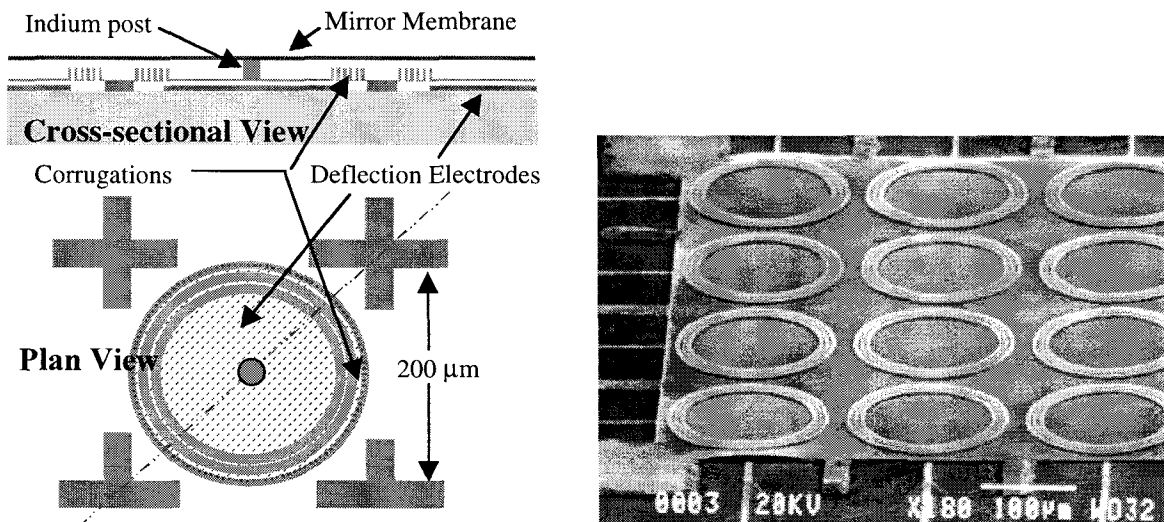


**Figure 5.** The schematic diagram above shows the operation of the piezo-driven MEMS microvalve. The SEM micrographs of the valve seat show the inlet and outlet openings (left) and a magnified view (right) of microfabricated corrugations by an opening that serve as a particle trap.



Some of the MEMS microvalve concepts being developed at JPL include a piezoelectrically-actuated microvalve<sup>7</sup> (Fig. 5), a micro isolation valve (fusible valve for one-time operation only) and a solenoid-actuated microvalve.

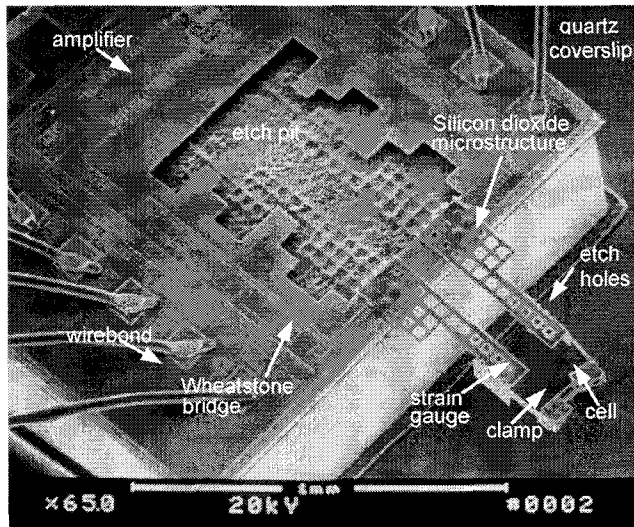
**Adaptive Optics:** NASA is currently in the planning stages for the Next Generation Space Telescope (NGST) which is expected to “see” farther into the Universe than the Hubble Space Telescope (HST) and also have a substantially lower mass per square meter at a comparable or lower cost than HST. Among the enabling technologies that will help NGST achieve these goals are small, low mass, deformable mirrors to be used in the auxiliary adaptive optics for precision wave front correction. The MEMS Technology Group is currently investigating the development of a novel MEMS-based deformable mirror technology<sup>8</sup> (paper 4091A-11 at this conference) consisting of a continuous membrane mirror with underlying electrostatic actuators for deflection (Fig. 6). The pixel-to-pixel spacing is as small as 200  $\mu\text{m}$ . The device is designed to have low



**Figure 6.** Schematic diagram showing the plan and cross-sectional views of a single pixel of the MEMS deformable mirror device is shown on the left. A scanning electron micrography of a 4x4 pixel array of the corrugated polysilicon intermediate mebrane is shown on the right.

influence between adjacent pixels, while providing a continuous optical quality mirror surface. It is designed to operate down to cryogenic temperatures (NGST requirement), with a maximum stroke of 4  $\mu\text{m}$  while being operated at an applied voltage of 160V, with a less than 10% influence function and a 1 nm/s surface stability. An array of 4x4 electrostatic actuators for the deformable mirror has been fabricated and characterized. The microfabricated actuator membrane has a vertical deflection of 0.3  $\mu\text{m}$  at 70 V.

**Bio-MEMS:** MEMS-based devices and systems are finding increasing application in the biological and biomedical fields. At NASA, these devices include biologically inspired sensors, actuators and power systems as well as devices for monitoring astronaut health as well as the environment in space-based human habitats such as the international space station. The Bio-MEMS activity at JPL has recently been initiated to pursue the above



**Figure 7.** Scanning electron micrograph of a MEMS heart cell force transducer. A single heart cell is mounted between two silicon dioxide clamps attached to microbeams. The cell contraction is measured by a strain gauge located at the base of one of the microbeams and forming one arm of a Wheatstone bridge. The signal from the bridge is amplified on chip and recorded using an off-chip data acquisition system.

NASA objectives. Bio-MEMS devices such as heart cell strain sensors<sup>9</sup> (Fig. 7) have been successfully fabricated and tested.

**MEMS-based In Situ Instruments:** MEMS Technologies have also been successfully utilized to develop miniature instruments for the *in situ* exploration of planetary bodies. Two examples of such instruments are:

**(a)** An Atmospheric Electron X-ray Spectrometer (AEXS)<sup>10</sup> that uses a microfabricated SiN membrane to encapsulate a miniature electron column. The membrane is electron-transmissive, i.e. it allows a high energy electron beam to propagate a short distance in atmosphere, generating characteristic x-ray fluorescence from samples placed near the AEXS. The x-ray emission is subsequently analyzed to determine the elemental chemical

composition of the sample.

**(b)** A Force Detected Nuclear Magnetic Resonance Spectrometer (FDNMRS)<sup>11</sup>. This is unique device that is especially suited for MEMS sizes and can perform chemical identification of organic compounds and water bearing minerals via their Nuclear Magnetic Resonance spectrum.

**MEMS Reliability:** As more and more MEMS devices make the transition from laboratory demonstrations to commercial products, the long-term reliability of these devices becomes a cause for concern. For space applications especially, device reliability is a critical issue and can in many cases be the single determinant of mission success or failure. The Reliability Assurance section at JPL is well equipped with state-of-the-art sample preparation and characterization tools such as high resolution optical microscopy, AFM, SEM and TEM, as well as specialized mechanical and electrical test and characterization equipment. The section supports not only the reliability needs of the MEMS Technology Group but outside organizations such as universities and MEMS foundries as well.

**Future Directions:** Consistent with national trends, the two main growth areas for the MEMS Technology Group are in the fields of Biotechnology and Nanotechnology as applied to NASA needs. Advanced research projects have been initiated in both of these fields for the development of novel bio-inspired devices as well as nanomachined sensors. Progress made in these areas by the Group will be reported at a subsequent conference.



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